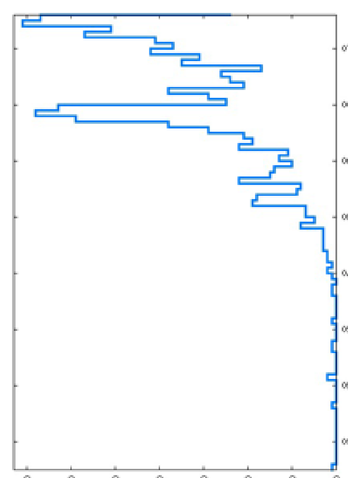

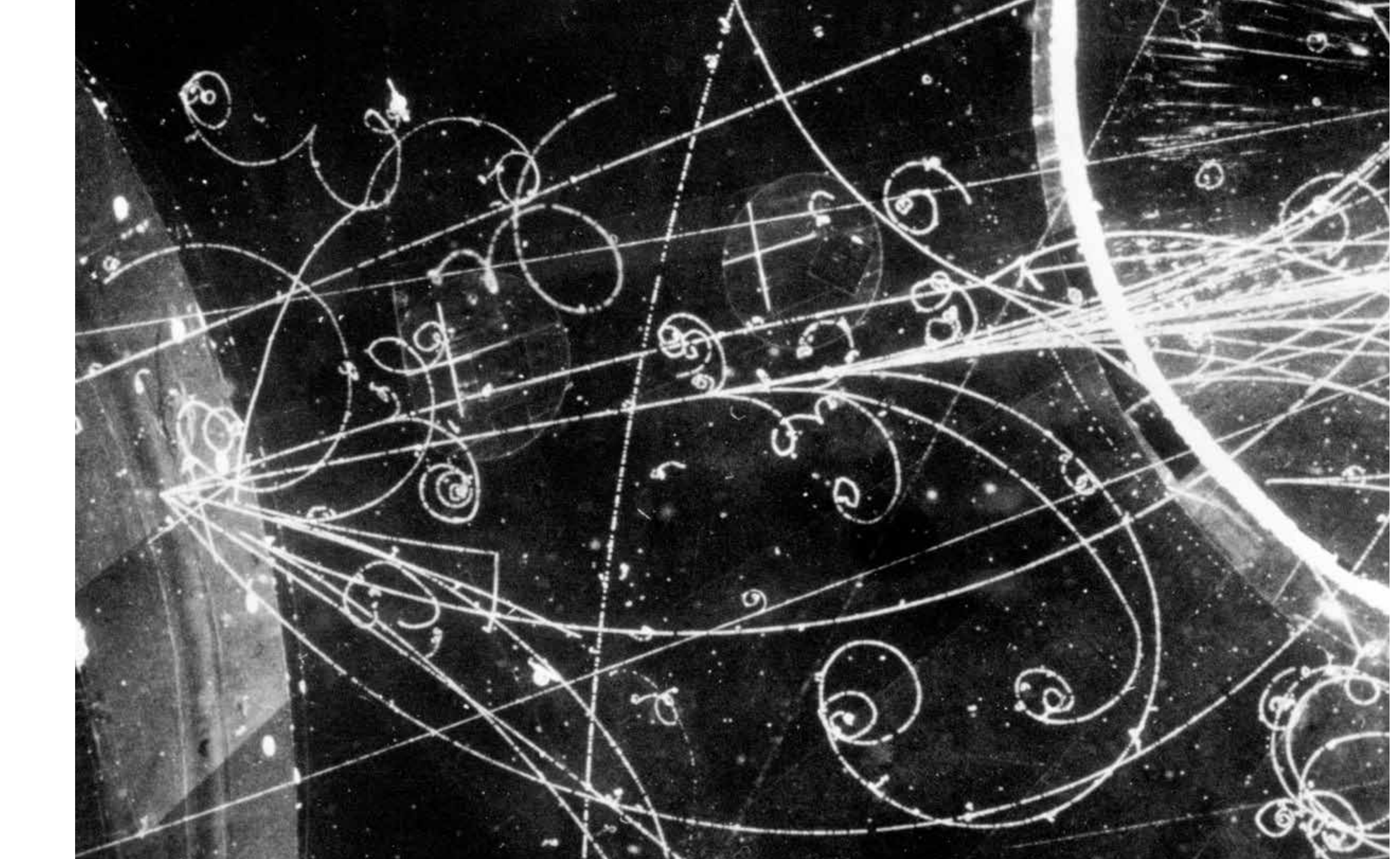

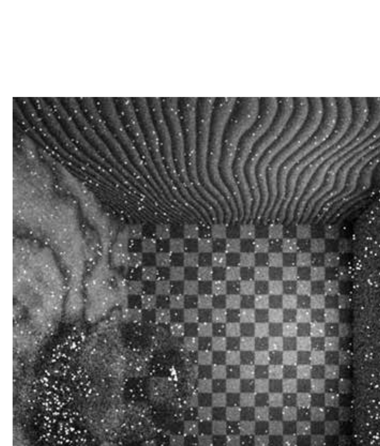

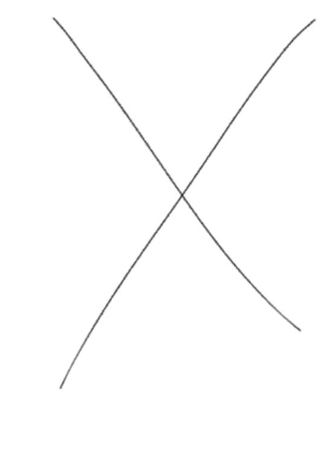

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REALITY IS ONLY A WORD

1. It Might be Weird but it Works!

Quantum mechanics[1] is the physics of the very small. The story I want to tell here will focus mainly on a peculiar feature of that world called **entanglement** and its implications for how we understand 'reality'. Erwin Schrödinger, one of the founding fathers of quantum theory, coined the term entanglement in 1935. He regarded it as "...*the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought." Certain aspects of quantum mechanics can appear weird, absurd even, yet it is an article of faith amongst physicists that quantum theory is the greatest human achievement of the 20th century.

It is both beautiful in its mathematical formulation and powerful in terms of its explanatory reach. Questions as diverse as why the sky is blue and the grass is green, to what makes rocks hard, to why the sun shines, all find their ultimate explanations in quantum mechanics. Its accuracy is unprecedented. There has never been a more finely tested physical theory[2]. Over the past hundred or so years it has been subjected to ever more ingenious and subtle experimental tests and its predictions have always been confirmed. Upon its validity rests the huge edifice of technology which defines modern life — it led directly to the invention of the transistor, a device which one way or another is behind all modern electronics. There would be no lasers without quantum mechanics nor would there be the nuclear magnetic resonance imaging technology so important in modern medicine. I could go on. In summary, quantum mechanics works!

So where's the weirdness? Well for one thing we're used to being able to visualise what's going on in our physical theories. But taking literally the quantum mechanical description of the atomic world, applying to it the visual grammar of our intuition, we find ourselves mired in a philosophical house of mirrors, encountering paradoxes at every turn. The problems arise from certain peculiar features of the quantum mechanical description of nature. There is the implication that an essential randomness is at work, at least in the sense that the answers to questions we can ask of the quantum world are in general and in principle random. This randomness seems not to have to do with a lack of complete knowledge of some deterministic mechanism at work 'behind the scenes', but is an inherent feature of how we are able to interface with the microworld. Another curious feature of the quantum formalism is the indirect way in which the current knowledge of a system, it's 'state', is encoded mathematically. This quantum mechanical 'state vector' is the central object of study and yet its status, beyond that of a calculational devise, is still hotly debated.

We'll explore these and other strange aspects of the quantum world and its formalism in what follows. I want to give as honest an account as possible of what makes quantum mechanics weird using essentially no mathematics but I also want to show you how physicists represent things in their actual work — I'm going to give you a genuine look at their symbolic language. So as not to obscure the

[1] I'll interchangeably use the terms quantum mechanics, quantum theory and quantum physics.
[2] In truth, quantum mechanics is regarded as nothing less that the correct framework for *all* of physics.

His concern now centred on the issue that if quantum mechanics is to be believed, in the sense that there are no hidden variables at work predetermining the measurement outcomes of Alice and Bob, then how can it be that the measurement outcome of Bob 'determines' that of Alice. Returning to our magic trick, how can it be that Bob inspecting his die from the top door and seeing a 6 *guarantees* that if Alice also inspects her die through the top door she must also see a 6 even though, working individually, choosing between the two doors at will they observe nothing but the expected randomness of a rolled die? To be fair to Einstein, I think its quite understandable that he chose not to believe that nature could be so strange! In another letter to Born, in 1948, he put it thus.

"Those physicists who regard the descriptive methods of quantum mechanics as definitive in principal would...drop the requirement for the independent existence of the physical reality present in different parts of space; they would be justified in pointing out that the quantum theory nowhere makes explicit use of this requirement. I admit this, but would point out: when I consider the physical phenomena known to me, and especially those which are being so successfully encompassed by quantum mechanics, I still cannot find any fact anywhere which would make it appear likely that (the) requirement will have to be abandoned. I am therefore inclined to believe that the description of quantum mechanics...has to be regarded as an incomplete and indirect description of reality..."

His point here is that the simple fact of Bob, on his distant galaxy, deciding to test his piece of quantum stuff for colour surely cannot "through some spooky action at a distance" determine the outcome of a colour test made by Alice on her piece of quantum stuff in a distant galaxy. Thus, though the quantum formalism doesn't seem to *need* to require preexisting properties, some form of instruction sets, to give rise to these properties, they *must* be there and so something is missing! Einstein's reasoning seems reasonable and yet the hard truth was that quantum mechanics seemed to be doing just fine without the so called 'hidden variables' (instruction sets) and to many Einstein appeared to be wasting his time on a purely philosophical question. As Wolfgang Pauli put it, somewhat uncharitably(!), in a letter to Born in 1954:

"One should no more rack one's brain about the problem of whether something one cannot know anything about exists all the same, than about the ancient question of how many angels are able to sit on the point of a needle. But it seems to me that Einsteins questions are ultimately always of this kind."

6. An Explanation of the Quantum Correlations?

It's actually rather easy to see how a satisfactory 'hidden variable' explanation *can* account for the observed correlations. We suppose that somehow the process of producing these entangled pairs produces pairs of pieces of quantum stuff that are in fact carrying instructions of how to respond to colour or shape measurements. In a single run, then, it might be that both pieces of the pair were carrying instructions for blue circle. Of course *we* don't have access to these instructions, they're *hidden*, so we can't say before Alice and Bob carry out measurements what the outcomes will be. But *nature* 'knows' that if Alice or Bob carry out a shape measurement they'll both observe the outcome circle and if they test for colour they'll find blue. If, then, in the process of producing thousands of such entangled pairs 25% of the time both pieces of quantum stuff carry with them those instructions for blue circle, 25% of the time for red circle, 25% of the time for blue square and 25% of the time for red square then this would reproduce the findings of Alice and Bob. Individually, 50% of the time when Alice or Bob test for colour they'd find blue and 50% of the time they'd find red. Likewise, when testing for shape they'd find circle

50% of the time and square 50% of the time. Thus, as required, their individual results would appear perfectly random. But, on those occasions that they both tested for colour or shape on two pieces of entangled quantum stuff, that is, they both tested for the same property on a single run of the experiment, they'd find that they always agreed and that 25% of the time they'd both observe red, 25% of the time blue, 25% of the time circle and 25% of the time square. All of this in perfect agreement with the experimental results as summarised in the table above.

So perhaps Einstein was right? Perhaps that's how it works and the quantum formalism is somehow missing these hidden variables working in the background. But how could we ever test for their existence? Remarkably, that question lay unanswered for about 30 years, until in 1964 John Bell made a startling discovery. But before we get to that let's round out our discussion of entanglement by seeing, at least symbolically, how quantum mechanics achieves what we've managed here with our hidden variables.

7. Quantum Mechanics Lesson 3 - Entanglement (II)

The pair of pieces of quantum stuff are entangled because they originate from a single piece in a particular way such that their state is represented by the following expression.

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|{\color{blue}\bullet}\rangle_A|{\color{blue}\bullet}\rangle_B - |{\color{red}\bullet}\rangle_A|{\color{red}\bullet}\rangle_B\right)$$

The A and B subscripts here denote Alice and Bob's piece of quantum stuff. This is the mathematical representation of the state of the pair of distantly separated pieces. Notice that we can't say that Alice certainly has a blue or red piece of stuff. The overall description is a sum of two possibilities. It's a superposition. It's like what we saw before with a state of definite colour being described as a superposition of the two possible shape states.

Now suppose Bob tests his piece of quantum stuff for colour and finds blue. This new information eliminates the red possibility from the description of the state leaving us with the pair described by the state $|{\color{blue}\bullet}\rangle_A|{\color{blue}\bullet}\rangle_B$ and we see then that Alice's piece of stuff must also have blue colour. If she tests for colour she is *sure* to find blue. On the other hand, this post Bob measurement state can also be written as

$$|{\color{blue}\bullet}\rangle_A|{\color{blue}\bullet}\rangle_B = \frac{1}{\sqrt{2}}\left(|\bigcirc\rangle_A + i|\square\rangle_A\right)|{\color{blue}\bullet}\rangle_B$$

which shows us that if Alice instead tests for shape then the result is entirely random. There's a 50% chance she'll find circle and 50% chance she'll find square. When they don't test for the same property there is no correlation.

We can also rewrite the original state in terms of shape states as follows (this is simply a matter of plugging in the expressions we saw earlier relating known colour state to superpositions of shape states).

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\bigcirc\rangle_A|\bigcirc\rangle_B - |\square\rangle_A|\square\rangle_B\right)$$

In this form we see, for example, that if Bob tests for shape and finds square then the updated description of the entangled pair is described by the state $|\square\rangle_A|\square\rangle_B$ and so it is clear that if Alice measures shape she too will find square.

8. John Bell's contribution

In the discussion of the EPR argument I focussed on Einstein's belief that there must exist some hidden variables accounting for the perfect correlations. This is often described as the assumption of **realism**. Einstein's insistence that physics be about 'what is'. The idea that things have properties whether or not we test for

those properties. To Einstein and his coworkers this requirement was the inevitable conclusion assuming the quantum results since they took it as self-evident that there could be no "spooky" communication between the two pieces of quantum stuff to orchestrate the observed results. This no causal influence assumption is called **locality**, and means that the test Bob chooses to make cannot influence Alice's stuff or vice versa. For Einstein there was no room for flexibility on this point. As I've already mentioned it was a fundamental principle in his own special theory of relativity. The consequences of causal influences travelling *faster* than light allow for a rather catastrophic breakdown in what could be called natural causality. Events in the future could influence those in the past! Einstein's relativity had banished the notion of instantaneous action-at-a-distance from physics and it was inconceivable that it would be reintroduced by quantum theory!

The EPR argument could thus be summarised as follows:

$$\begin{matrix}\text{Quantum}\\ \text{Mechanics}\end{matrix} + \text{Locality} \implies \begin{matrix}\text{Hidden}\\ \text{Variables}\end{matrix}$$

Note that this, of course, is an *argument* based on certain strong prejudices. One, as just mentioned, was locality and the other was realism, that we can think about reality in the atomic domain in the same terms as we can that of everyday experience.

Now recall the explanation we gave of the perfect correlations in terms of each entangled pair carrying with it one of four instruction sets, blue or red circles and blue or red squares. This is an explanation which satisfies the requirements both of locality and realism. In 1964 John Bell, a physicist at CERN, thought more deeply about this experimental arrangement. By slightly complicating it, effectively considering the possibility of testing for one of *three* properties, he proved a remarkable result. Quite generally, independent of quantum mechanics itself, he considered what correlations could arise in such a setup by just assuming what EPR held so dear, namely, locality and realism. He obtained a bound on the possible correlations, called **Bell's inequality**. Then, applying the quantum formalism to his setup he demonstrated that quantum mechanics predicted a *violation* of these bounds! Effectively what he demonstrated could be expressed as:

$$\begin{matrix}\text{Hidden}\\ \text{Variables}\end{matrix} + \text{Locality} \implies \begin{matrix}\textbf{Not}\ \text{Quantum}\\ \text{Mechanics}\end{matrix}$$

This opened up the possibility of carrying out an experimental test of whether Einstein was right. A test of whether nature was both local and realistic!

It was a happy coincidence that Bell's analysis appeared just as the technology required to realise such an experiment was emerging. Still, it wasn't until the french experimental physicist Alain Aspect's famous 1982 experiment that it was confirmed that, indeed, **nature obeys quantum mechanics** and therefore one of locality and realism must be given up.

Bell's result is not difficult to derive, it doesn't rely on any complicated mathematics. However it would require us to go beyond our simple colour/shape model of quantum stuff. Fortunately though, in 1989, Daniel Greenberger, Michael Horne and Anton Zeilinger discovered another way of demonstrating the fact that the combination of hidden variables and locality is not consistent with quantum mechanics and which it *is* possible to explain using our simple version of quantum theory. In any case this is a stronger and more dramatic result than the original Bell argument so don't feel short changed!

9. Quantum Mechanics Lesson 4 - The GHZ experiment

We now need three helpers, Alice, Bob and Charlie each alone in three far-flung galaxies to ensure there can be no question of one influencing the other. Each does exactly as Alice and Bob did for us before. Upon receiving a piece of quantum suff they randomly choose to test for colour or shape and record their result. As before, each observes an apparently random set of results. Having collected plenty of results they return to earth to compare what they found. It happens that they are unanimous in preferring (on purely aesthetic grounds) circles over squares and blue over red so blue and circle are deemed 'good'. Thanks to this preference they notice a remarkable pattern in their results.

Whenever two of them tested for shape and one for colour then they either had 0 or 2 'good' outcomes between them.

Now let's pause for a minute and think about what implications this might have in terms of our assumptions of locality and realism. Locality is of course dealt with by the fact that Alice, Bob and Charlie were all testing randomly on far flung galaxies. There was no chance (barring some sort of faster than light signalling) that they were in any way influencing each other. The realism assumption is more interesting. This amounts to the notion that the instructions of how to respond to whatever tests were performed were carried with the pieces of stuff to Alice, Bob and Charlie. Let's say the 'goodness value' of blue is 1 and 0 for red and that likewise the goodness value of circle is 1 and 0 for square. The three possible test combinations are exhibited in the following table.

Alice	Bob	Charlie
Colour	Shape	Shape
Shape	Colour	Shape
Shape	Shape	Colour

So, for example, it could be that Alice made a colour measurement whilst Bob and Charlie both carried out shape tests. In this case, then, the instructions being carried with the three pieces of quantum stuff arriving respectively at Alice, Bob and Charlie must be such that if Alice observed the outcome blue (good), whilst the result of Bob's shape test was circle (good) then we know that Charlie's shape test must have the outcome square (not good) ensuring a total of 2 good outcomes. Similarly, if Alice had instead found red (not good) whilst Bob had found square (not good) then again, to respect the observed correlations, the result of Charlie's shape test is determined to be square (not good) ensuring a total of 0 good outcomes. By the assumption of realism, each cell in the row has a goodness value, 1 or 0, and the observed correlations require the total for the row to be 0 or 2. But of course the type of experiment being carried out respectively by Alice, Bob and Charlie is in each case decided on the toss of a coin long after the pieces of quantum stuff have left earth and so it could also have been that Alice tested for shape, Bob for colour and Charlie for shape as in the second row or that both Alice and Bob chose to test for shape and Charlie for colour as in the third row. The assumption of realism, the notion that instruction sets are being carried with the individual pieces of quantum stuff, together with the fact that the respective measurement decisions are made randomly after the three pieces of entangled quantum stuff have left earth thus means that each cell in *each* row of the table has a goodness value of 0 or 1 and that summing these across the rows always gives the result 0 or 2. But this means that in the whole table the total goodness value of all the cells is even.

Now, notice that there are an even number, 6, of shape cells. This forces the sum of the goodness values of the three colour cells also to be even (an even number is either the sum of two evens or two odds, not a mixture). In other words we can already say with 100% certainty, based on the realist assumption, that *in any test in which Alice, Bob and Charlie each test for colour the total amount of good must be even.*

Feeling chuffed with themselves for this bit of Sherlock Holmes sleuthing they return to their data and scan for all the times they all tested for colour on the same triplet of pieces of quantum stuff. Dumbstruck they see that the data tells *precisely the opposite* story!

Whenever all of them tested for colour they either had 1 or 3 'good' outcomes between them.

Quantum mechanics predicts these two outcomes, utterly incompatible based on the twin assumptions of locality and realism, and experiments have confirmed the predictions of quantum mechanics.

It is a great irony that John Bell, who set in motion these tests of Einsteins dear principles of locality and realism, strongly believed that Einstein *should* have been right! Reflecting on the results of the original Aspect experiments he expressed his disappointment thus:

"So for me, it is a pity that Einstein's idea doesn't work. The reasonable thing just doesn't work."

The quantum symbolics of the GHZ experiment are as follows. The three particles are prepared in a state, let's denote it $|GHZ\rangle$, which, expressed purely in terms of colour states looks like this,

$$|GHZ\rangle = \frac{1}{2}\left(|{\color{blue}\bullet}\rangle_A|{\color{blue}\bullet}\rangle_B|{\color{blue}\bullet}\rangle_C + |{\color{blue}\bullet}\rangle_A|{\color{red}\bullet}\rangle_B|{\color{red}\bullet}\rangle_C + |{\color{red}\bullet}\rangle_A|{\color{red}\bullet}\rangle_B|{\color{blue}\bullet}\rangle_C + |{\color{red}\bullet}\rangle_A|{\color{blue}\bullet}\rangle_B|{\color{red}\bullet}\rangle_C\right).$$

But this state can also be written using 1 colour state and 2 shape states as,

$$\begin{aligned}|GHZ\rangle &= \frac{1}{2}\left(|{\color{blue}\bullet}\rangle_A|\square\rangle_B|\bigcirc\rangle_C + |{\color{blue}\bullet}\rangle_A|\bigcirc\rangle_B|\square\rangle_C + |{\color{red}\bullet}\rangle_A|\bigcirc\rangle_B|\bigcirc\rangle_C + |{\color{red}\bullet}\rangle_A|\square\rangle_B|\square\rangle_C\right)\\ &= \frac{1}{2}\left(|\bigcirc\rangle_A|{\color{blue}\bullet}\rangle_B|\square\rangle_C + |\square\rangle_A|{\color{blue}\bullet}\rangle_B|\bigcirc\rangle_C + |\bigcirc\rangle_A|{\color{red}\bullet}\rangle_B|\bigcirc\rangle_C + |\square\rangle_A|{\color{red}\bullet}\rangle_B|\square\rangle_C\right)\\ &= \frac{1}{2}\left(|\square\rangle_A|\bigcirc\rangle_B|{\color{blue}\bullet}\rangle_C + |\bigcirc\rangle_A|\square\rangle_B|{\color{blue}\bullet}\rangle_C + |\bigcirc\rangle_A|\bigcirc\rangle_B|{\color{red}\bullet}\rangle_C + |\square\rangle_A|\square\rangle_B|{\color{red}\bullet}\rangle_C\right)\end{aligned}$$

I leave it as an exercise to confirm that the equality of each of these representations of the *same* state do indeed lead to the results Alice, Bob and Charlie recorded.

10. What Does It Mean?

In the discussion above I have barely entertained the possibility that some sort of 'spooky action at a distance', some kind of super-luminal signalling between the components of an entangled quantum system could be at work. This reflects my own personal view, and I must now come clean and admit that there is an active body of researchers, typically, but not exclusively, philosophers of science, for whom the universal validity of classical realism, the objective reality of properties of things, is sacrosanct. John Bell, who was most definitely a physicist, was in this camp and is still today, 26 years after his untimely death, the champion of their cause. They hold to the notion that the goal of science generally and physics in particular must be to provide a coherent account of *what is*. Not only is the classical notion of reality taken to be a self-evident fact of nature, without it, they believe physics must surely fall short of the standards set for itself by its own historic legacy. To quote Tim Maudlin, a prominent philosopher of science, *"I am only interested in physics insofar as it attempts to provide a clear and comprehensible account of*

what the physical world is." Thus, to these researchers, an entangled pair of pieces of quantum stuff are genuinely *physically* connected, regardless of how far apart they are, and carrying out a measurement on one piece indeed influences the other and this influence propagates instantaneously. The burning question is, of course, what are the implications for Einstein's relativistic description of space-time? To date this theory has never been found to be experimentally wanting and, being the inevitable consequence of a few very simple principles, feels solid. Moreover, it is surely significant that, apparently as a matter of principle, the 'strange communication' at work in entanglement cannot possibly be harnessed to usefully transfer information between two separated locations.[8] The followers of John Bell also point disparagingly at the prominent roles of observers and measurement in the quantum formalism. Are not observers governed by the laws of quantum mechanics too? Bell himself felt a need for a theory that *"neither needs nor is embarrassed by an observer."*

Beyond those physicists focused on the philosophical foundations of quantum mechanics there is general acceptance that it is the assumption of realism which has to be given up. Besides the fact that the 'spooky action at a distance' is a magic out of our reach, they might also point to various other experimentally verified predictions of quantum mechanics, such as the violation of the so-called Leggett inequalities and the confirmation of the Kochen-Specker theorem all of which tend to support the idea that the classical notion of realism is not tenable at the atomic scale. I think many of them would agree with Feynman who in a 1983 BBC interview[9] suggested that clinging onto our intuitively satisfying notion of a reality 'out there', independent of us, is a *"deep prejudice...from being so used to large scale behaviour"*. Even if they don't explicitly acknowledge it, they are adopting Bohr's position of physics being about *what can be said* rather than *what is*. Of course, giving up the universality of classical realism raises some serious and difficult questions. Perhaps most pressing among them is how it is that the realism we are familiar with emerges from the 'unreality' at the atomic scale?

Amongst those physicists who more or less align themselves with Bohr's philosophy and are concerned with the foundations of quantum theory, the remarkable success of the quantum formalism, with the observer and measurement so tightly integrated therein, hint at new ways of understanding our role in the construction of physical theories, of what, indeed, physical theories really *are*. Perhaps we should think of them rather as maps with which we may navigate the world around us rather then the world itself. This may seem like a retreat from the grand project of science as the unlocking of Nature's hidden mechanisms. I don't think so. I rather suspect that humans have gotten way ahead of themselves. Intoxicated by the undeniably impressive progress of science to date we foolishly believe that more of the same will continue to bear fruit and at the same remarkable rate. I suspect that the lesson of what we've learnt of the quantum world and more specifically of how we've been forced to interface with it is telling us that a radical change of perspective is required. We are not and cannot be separated from the world around us.

[8]This is simple to appreciate — take the case of a pair of gloves each one of which is placed blind into a box as discussed earlier. Upon opening his box in Melbourne Bob knows what's in Alice's box instantly. But, without calling Alice by some conventional (slower than light speed!) means this information cannot usefully be used. For Alice, without receiving such a call from Bob, there is still a 50:50 chance of finding a right or left hand glove in her box. To her, nothing has changed.

[9]"Physics is fun to imagine" can be viewed at `https://www.ted.com/talks/richard_feynman`

At the end of the interview with Feynman I quoted from earlier he said something which resonates deeply with my own personal 'faith' and which I feel is an appropriate way to end our story.

"I think Nature's imagination is so much greater than man's she's never going to let us relax."